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DEVELOPMENT OF RIGID STRUCTURES USING CROSS-SECTIONAL COLUMNS WITH STANDARD MATERIALS FOR WOODEN FRAME CONSTRUCTION

Ryota Kawashima[1], Satoshi Onishi[2], Hideyuki Nasu[3]

ABSTRACT: The purpose of this research is to develop a wooden rigid frame structure using standard materials and hardware. Using wooden frame construction method columns, the columns are fastened to each other in a cross-shaped cross-sectional view to form a cross-sectional column. The cross-sectional columns are used for the column portion of the gate-type rigid frame to form a wooden rigid frame structure. The parameters are the method of joining the columns and the distance between the screws for timber structures. The test results showed that the initial stiffness was low for all the tested specifications. This is due to compression perpendicular to the grain in the wood. Therefore, the current specifications have low initial stiffness, making it difficult to realize a cross-column rigid-frame structure. Therefore, it is effective to reduce compression perpendicular to the grain in the wood to improve the initial stiffness. Misalignment between columns also has a significant effect on initial stiffness, and it is recommended to use adhesives to eliminate misalignment between columns. However, since the distance of screw fixation was unknown, we tested the performance of two-sided shear with adhesive screw fixation and found that the adhesive performed better when the columns were fixed with half-screws than with full screws.

KEYWORDS: Wooden rigid frame structure, Cross-sectional column, Standard materials,

1 RIGID FRAME STRUCTURE TEST

1.1 INTRODUCTION

Modern wooden rigid-frame structures require large-section structural materials, high-strength special hardware for joints, and special factory facilities. Therefore, we propose the Cross-Sectional Column Rigid Frame Structure for the purpose of developing a wooden rigid frame structure that can be constructed onsite using standard materials and hardware that are generally available in the market. The cross-sectional column rigid frame structure can be constructed onsite without using special hardware for joints and can be used to make a wooden house that is open plan and easy to change the layout of rooms. In addition, by arranging the columns in a crisscross pattern, it is possible to eliminate the corner parts of columns that often protrude from walls and cause dead spaces, as is the case with large-section columns.

1.2 SUMMARY OF RESEARCH

The test specimens were formed using standard materials and hardware in general circulation (Fig. 1, 2, 3). For the joint type 400 mm, the distance between the screws that fasten the columns was set to 400 mm. For the joint type 200 mm, the distance was set to 200 mm. For the adhesive combination type, the distance of 400 mm was used, and an adhesive was also used to join the columns together (Table 1). In this study, we compared the structural performance with that of a single-sided plywood bearing shear walls. In addition, we compared and verified the differences in construction workability and structural performance by changing the method of joining the columns and the distance of the screws.

***Table 1** Specimen specifications*

Specimen name	Adhesive	Joining method	Distance
Joint type 400 mm	×	Screw for timber structures	400 mm
Joint type 200 mm	×	Screw for timber structures	200 mm
Adhesive combination type	○	Screw for timber structures	400 mm

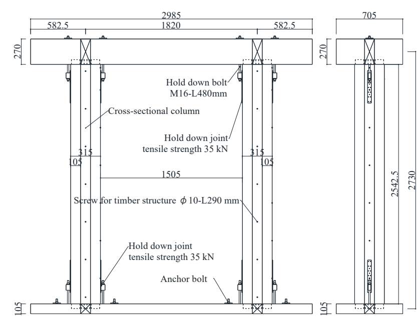

***Fig. 1** Specimen overview (left: front, right: side)*

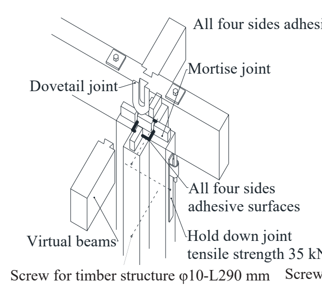

***Fig. 2** Joint details*

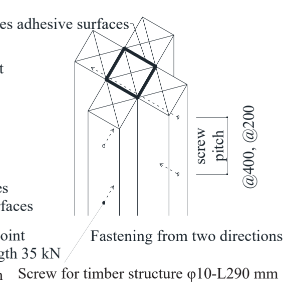

***Fig. 3** Cross-sectional column*

[1] Ryota Kawashima, Graduate School, Nippon Institute of Technology, JAPAN, ryota.kawashima13@gmail.com

[2] Satoshi Onishi, Asst., M. in Eng., Nippon Institute of Technology, JAPAN, onishi.satoshi@nit.ac.jp

[3] Hideyuki Nasu, Prof., PhD. in Eng., Nippon Institute of Technology, JAPAN, hideyuki.nasu@nit.ac.jp

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1.3 EXPERIMENTAL RESULT

Fixed photos are shown in Fig. 4, 5. The wall magnification was calculated for two wall lengths, L, with a distance between columns of 1820 mm and a width of 630 mm, which is the width of the two cross columns. The test results for each specification and single-sided plywood[2)] are shown in Table 2, the load-displacement curve is shown in Figure 6, and the average displacement between the columns is shown in Figure 7. Compared with the face-material bearing walls, all specifications had lower initial stiffness, and the allowable shear capacity (Pa) was determined by the load (Pr) at a specific deformation angle. The test results for each specification and the reason for the low initial stiffness of the 400 mm and 200 mm joints are thought to be that the columns were misaligned so much that the corners of each column were wedged into the framing members (Fig 8), prevented the hold down joint from demonstrating its capabilities. In the case of the adhesive bonding type, the hold-down joint was able to demonstrate its capabilities (Fig. 9), and there was no misalignment between the columns, however, the corner of the cross-shaped columns (Fig. 10, 11) was embedded into the cross members, which increased the interlaminar displacement. Therefore, it is necessary to suppress the penetration to improve the initial stiffness.

Fig. 4 *Before shearing test*

Fig. 5 *After shearing test*

Table 2 *Structural performances*

	Joint type 400 mm	Joint type 200 mm	Adhesive combination type	Single-sided plywood
K [kN/mm]	0.16	0.21	0.33	0.64
Pmax [kN]	19.77	24.56	29.36	16.62
Pu [kN]	17.31	21.40	25.50	14.84
E [kN･mm]	2260	2864	3669	1212
μ	1.73	1.83	2.38	4.05
Ds	0.63	0.61	0.51	0.37
2/3Pmax [kN]	13.18	16.37	19.57	11.08
Py [kN]	12.13	14.08	17.13	11.54
Pr [kN]	**4.13**	**5.23**	**8.82**	12.11
Pu*(0,2/Ds) [kN]	5.43	7.01	9.91	**7.91**
Pa [kN]	4.13	5.23	8.82	7.91
times	1.15	1.46	2.47	2.21
times	3.34	4.23	7.14	
mm	7.02	4.40	0.05	

Bold number lowest specification

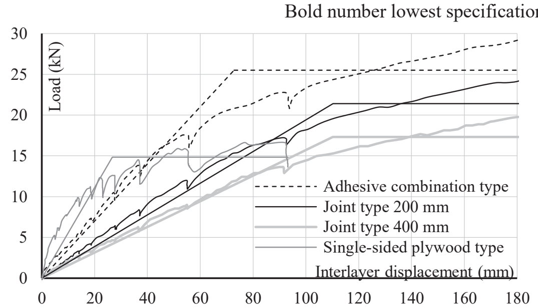

Fig. 6 *Experimental and analysis load-displacement curves*

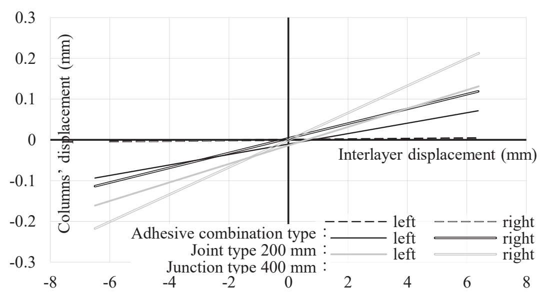

Fig. 7 *Interlayer-columns' displacement relationship*

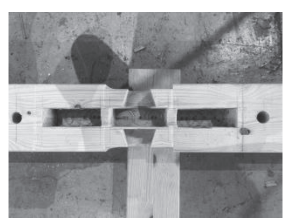

Fig. 8 *Compression perpendicular to the grain (Joint type 400 mm)*

Fig. 9 *Deformation of joint (Adhesive combination type)*

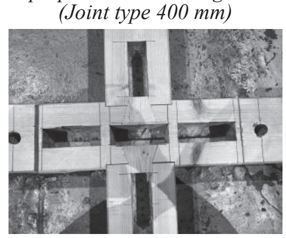

Fig. 10 *Compression perpendicular to the grain (Adhesive combination type)*

Fig. 11 *Deformation of sill (Adhesive combination type)*

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1.4 RESULT

"wallstat" was used to analyze a house with cross columns and a house with a frame construction method, but with a similar wall volume and plan. (Fig. 12, 13) As a result, the cross-steel frame structure did not collapse even under the same seismic motion (Fig. 14, 15). The load displacement curves are shown in Fig. 16, 17. This indicates that if the cross-sectional column rigid structure becomes more resistant to earthquakes, it can be used in many safe and easy-to-retrofit houses because of its use of standardized materials.

1.5 CONCLUSION

Although structural performance improves as the deviation between columns decreases, it is considered difficult to achieve the current cross-sectional column rigid structure due to the low initial stiffness. To improve the initial rigidity, it is effective to prevent misalignment between the pillars and to reduce the compression perpendicular to the grain of the wood.

If the cross-sectional column rigid frame structure can be made more resistant, many safe and easy-to-retrofit houses will become widely available because of the use of standard lumber.

2 SHEAR TEST

2.1 INTRODUCTION

Misalignment between columns, which is thought to have a significant effect on the initial stiffness of Cross-Sectional Column Rigid Frame Structure, can be solved by using adhesives. However, the structural performance of the glued and screwed structure has not been clarified. Since the optimum distance for fastening screws is also unknown, tests were conducted to clarify the structural performance and press-fastening performance when adhesive is applied, and screws are fastened. The parameters were the difference in the screws, the method of press-fastening, and the number of screws.

2.2 SUMMARY OF RESEARCH

The test specimens were not cross-shaped columns, but three 105 mm square, 900 mm long columns arranged side by side to resemble wall columns. The specimen was a two-sided shear specimen and the joint length between the columns was 800 mm (joint area 84,000 mm^2). For between the column's joints, Φ10-L290 mm full-threaded screw for timber structures (trade name: Panelead X, full-threaded screw) or Φ10-L290 mm half-threaded screw for timber structures (trade name: Panelead S, half-threaded screw) and an adhesive (water-based polymer isocyanate-based) were used. The specimens were glued to the base material and secured with screws from one direction. Screws were used for simple press-fixing from one direction to facilitate adhesion in the field. Parameters were the presence or absence of adhesive, method of press-fastening, number of screws (one or two) and screw type (full or half thread). Details of the test specimens are shown in Figure 18.

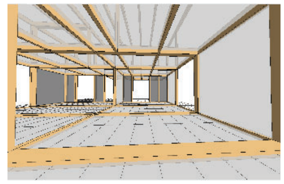

Fig. 12 *Inside view of the single-sided plywood type*

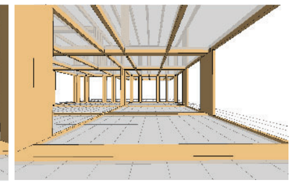

Fig. 13 *Inside view of the cross-sectional column type*

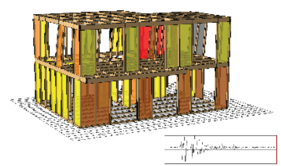

Fig. 14 *Analysis of the single-sided plywood type*

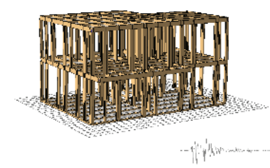

Fig. 15 *Analysis of the cross-sectional column type*

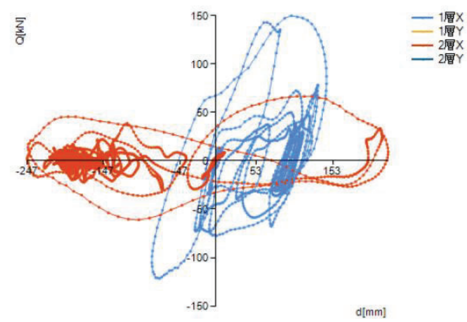

Fig. 16 *Load-displacement curves (single-sided plywood type)*

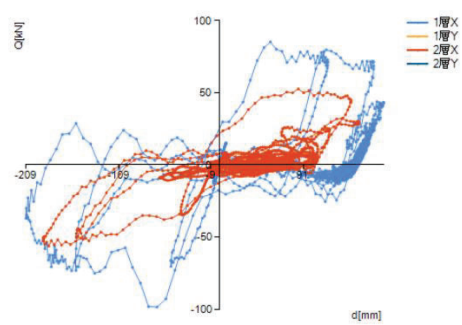

Fig. 17 *Load-displacement curves (cross-sectional column type)*

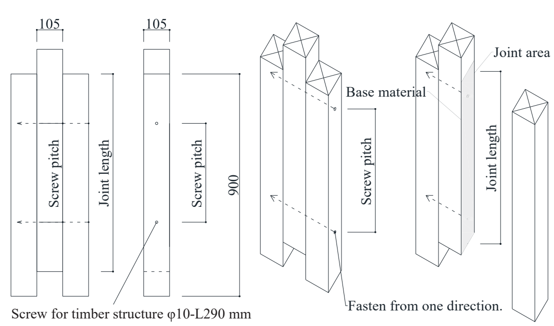

Fig. 18 *Specimen overview*

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Specification 1 (full-threaded screws 400 mm adhesive) was made by fastening two full-threaded screws at 400 mm using an adhesive to join the columns together (Fig. 19). Specification 2 (half-threaded screws 400 mm adhesive) consists of two threaded screws fastened together with adhesive at 400 mm. A comparison of the structural performance of the different screws with Specification 1 is presented. Specification 3 (one full-threaded screw adhesive) was achieved by fastening one full- threaded screw in combination with an adhesive (Fig. 20). Specification 4 (one half-threaded screw adhesive) uses one half-threaded screws glued together with an adhesive. A comparison of the structural and compressive performance of the different threaded screws with specification 3 is presented. Specification 5 (full-threaded screws 400 mm compression) is the same specification as Specification 1, but full-threaded screws were removed before the test (Fig. 21, 22). Specification 6 (half-threaded screws 400 mm compression) is the same specification as Specification 2, but the half- threaded screws were removed before the test. It is compared with specification 5 to verify the difference in compressive performance due to the different threaded screws. Specification 7 (pressure tightening) was glued using a pressure tightener without screws and with adhesive only (Fig. 23, 24). The differences in pressure-compression performance are clarified by comparison with specifications 5 and 6.

Specification 8 (static) was static without screws and with adhesive only, in an upright position (Fig. 25). It reproduced the most severe situation where no pressure tightening was possible. Specification 9 (full-threaded screws 400 mm) was made by fastening two full-threaded screws at 400 mm without the use of adhesive. Specification 10 (half-threaded screws 400 mm) was made by fastening two half- threaded screws at 400 mm without the use of adhesive. This specification is compared with specification 9 to verify the difference in structural performance between full-threaded screw and half-threaded screw (Fig. 26). Fixed photos are shown in Fig. 27, 28. Details of each specification are given in Table 3.

Table 3 *Details of each specification*

Specification	Joint length (mm)	Distance(mm), number of screws	Joining conditions
1	800	400, 2	Full-threaded screws+ adhesives
2		400, 2	Half-threaded screws+ adhesives
3		-, 1	Full-threaded screw+ adhesives
4		-, 1	Half-threaded screw+ adhesives
5		400, 2	Full-threaded screws+ adhesives
6		400, 2	Half-threaded screws+ adhesives
7		-, -	Adhesives ⇒ static
8		-, -	Adhesives ⇒ pressure tightening
9		400, 2	Full-threaded screws only
10		400, 2	Half-threaded screws only

Fig. 19 *400 mm adhesive*

Fig. 20 *One threaded screws adhesive*

Fig. 21 *removing screws*

Fig. 22 *Screws removed*

Fig. 23 *Applying adhesive*

Fig. 24 *Pressure tightening*

Fig. 25 *Static*

Fig. 26 *Difference in screws*

Fig. 27 *Before shearing test*

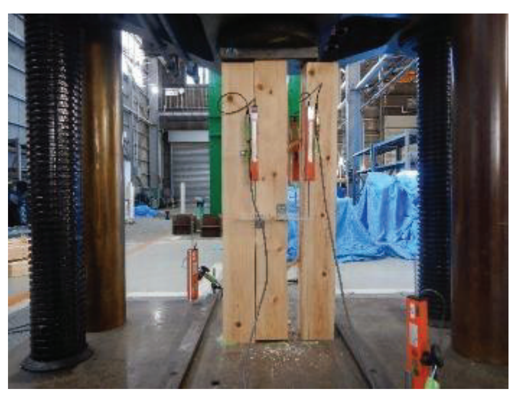

Fig. 28 *After shearing test*

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Tests were conducted using a 200-ton universal testing machine to test the two-sided shear of the screws. A compressive force was applied in the vertical direction, and the relationship between the load and the displacement between the columns was measured. The force was applied monotonically at a rate of 0.2 kN/s. After the adhesive peeled off or the wood near the adhesive broke, the force fell below 0.8 Pmax, but the force was applied up to 90 mm of displacement between the columns to check the bearing capacity of the screws. The relative displacement between the columns was measured at four locations (front, back, left, and right) to confirm the displacement between the columns. The displacement of the hydraulic plate was also measured at two locations, one at the front and the other at the back. Fig.29, 30 shows the installation diagram of the test specimen and the positions of the displacement transducers.

In the Cross-Sectional Column Rigid Frame Structure experiment, two strain gauges were affixed to each of the four upper and lower hold down bolts, which were subjected to tensile forces in the pulling direction, and axial forces were measured. The results showed that on the compression side, the timber was embedded and almost no axial force was applied. On the tension side, a maximum tensile axial force of approximately 70 kN was detected. Therefore, the primary check was whether 70 kN was exceeded before misalignment displacement between the columns occurred in this convex test. The strain measurement locations are shown in Fig. 31 and the axial force - interlaminar displacement curves averaged over four strain gauges on the column head and column leg sides respectively are shown in Figs. 32, 33.

The target value of the convexity test was determined based on the shear force and the misalignment between columns measured and detected in the sectional column rigid frame structure experiment. since the misalignment between columns at 1/15 rad. was 7 mm, the target value of the convexity test was set at 70 kN at Pmax and the bearing capacity at 7 mm misalignment between columns was also confirmed. The target value for the convexity test was set at 70 kN at Pmax. Since the displacement due to sudden failure was large, the bearing capacity at a misalignment of 7 mm was considered to change, and the bearing capacity at a misalignment of 20 mm was also checked to confirm the maximum bearing capacity of the screw.

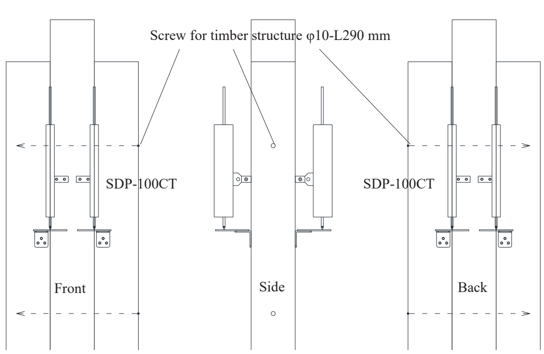

Fig. 29 *Displacement meter installation position*

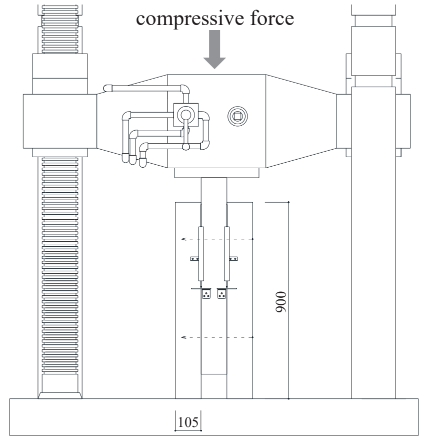

Fig. 30 *Test object installation diagram*

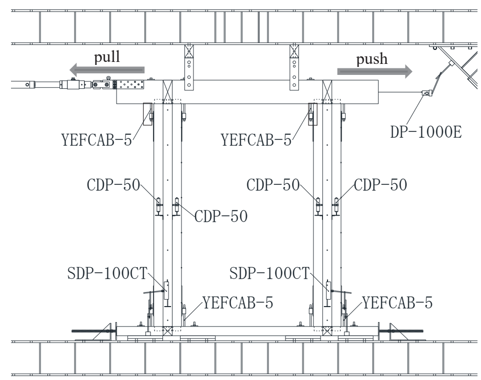

Fig. 31 *Displacement meter installation position*

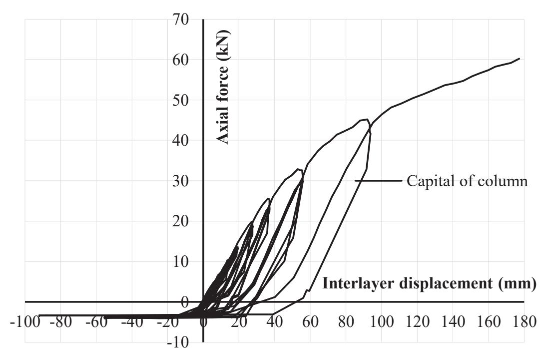

Fig. 32 *Axial force-displacement curves*

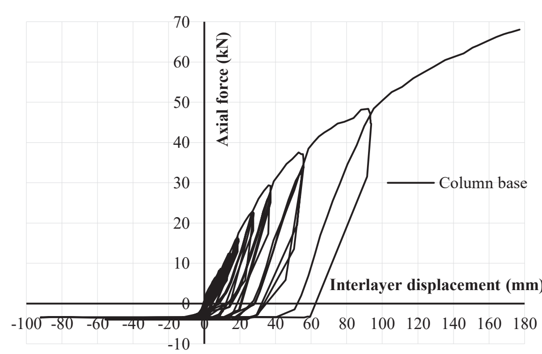

Fig. 33 *Axial force-displacement curves*

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2.3 EXPERIMENTAL RESULT

The load-column misalignment curves of the test results are shown in Fig. 34-37, the test values in Tables 4-12, and Fig graphs of the fracture properties in Fig. 38-41. Pmax exceeded the target value of 70 kN for all specifications. The final fracture was caused by wood fracture near the adhesive surface (Fig. 40 and 41). The bearing capacity of the screws showed approximately 35 kN at 7 mm misalignment and 50 kN at 20 mm misalignment. Although wood snags and knots caused variations in the bearing capacity of the screws, the difference in the bearing capacity of two-sided shear between full and half screws was almost negligible. With respect to the n3 half-thread one-unit adhesion, the test was terminated because no misalignment between the columns occurred and the convex part of the specimen buckled locally. Therefore, the average of the two specimens was obtained by excluding them from the average.

A few specimens had gaps when glue was applied and screwed down, and peeling of the glue occurred, but one opposite side was press-compacted and Pmax showed a high value (half-screw 400 mm adhesive n1). The shear capacity at the bonded area was determined from the shear reference strength of the timber and compared with Pmax, which was about half the shear capacity of the timber when simple compaction was carried out using screws. When screws were not used, the values were lower than the shear strength of wood. Therefore, it is thought that simple compaction using screws may be possible. Since Pmax is higher for half-threaded screws than for full-threaded screws, the use of half-threads is a good choice for simple press-fastening, but it is necessary to consider the length of the screws so that the threads do not come to the bonding surface between the columns. If shear force is applied to the material, a screw can be used as a dowel to bear the shear force and prevent brittle fracture.

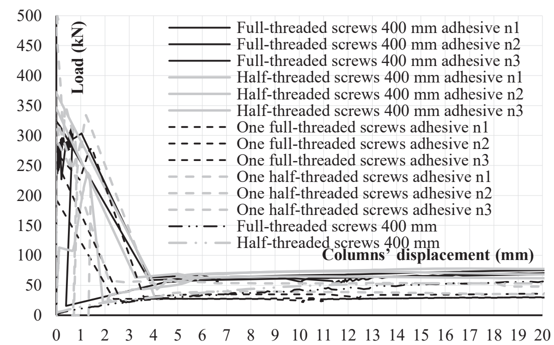

Fig. 34 *Load-displacement curves*

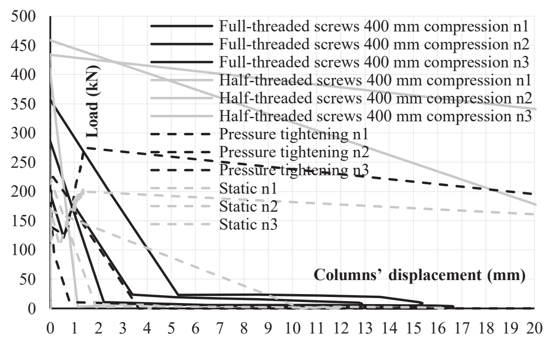

Fig. 35 *Load-displacement curves*

Table 4 *Full-threaded screws 400 mm adhesive*

Item	Unit	n1	n2	n3	Ave.
Pmax	kN	315.88	303.28	324.84	314.66
Fs	kN	504.00	504.00	504.00	504.00
Ratio to Fs	%	62.67	60.17	64.45	62.43
P(δ=7mm)	kN	61.44	63.72	61.24	62.13
P(δ=20mm)	kN	72.96	75.16	67.84	71.98

Table 5 *Half-threaded screws 400 mm adhesive*

Item	Unit	n1	n2	n3	Ave.
Pmax	kN	238.08	350.64	372.84	320.52
Fs	kN	504.00	504.00	504.00	504.00
Ratio to Fs	%	47.23	69.57	73.97	63.59
P(δ=7mm)	kN	68.84	70.32	63.44	67.53
P(δ=20mm)	kN	77.16	68.16	62.00	69.10

Table 6 One full-threaded screw adhesive

Item	Unit	n1	n2	n3	Ave.
Pmax	kN	261.24	280.12	196.12	245.82
Fs	kN	504.00	504.00	504.00	504.00
Ratio to Fs	%	51.83	55.57	38.91	48.77
P(δ=7mm)	kN	27.72	34.80	27.36	29.96
P(δ=20mm)	kN	29.96	36.08	30.16	31.97

Table 7 One half-threaded screw adhesive

Item	Unit	n1	n2	n3	Ave.*
Pmax	kN	314.48	333.68	511.52	324.08
Fs	kN	504.00	504.00	504.00	504.00
Ratio to Fs	%	62.39	66.20	101.49	64.30
P(δ=7mm)	kN	53.56	39.64	-	46.60
P(δ=20mm)	kN	48.08	34.84	-	41.46

*Except n3

Table 8 Full-threaded screws 400 mm compression

Item	Unit	n1	n2	n3	Ave.
Pmax	kN	284.92	358.48	201.64	281.68
Fs	kN	504.00	504.00	504.00	504.00
Ratio to Fs	%	56.53	71.12	40.00	55.88

Table 9 Half-threaded screws 400 mm compression

Item	Unit	n1	n2	n3	Ave.
Pmax	kN	460.08	434.96	434.12	443.05
Fs	kN	504.00	504.00	504.00	504.00
Ratio to Fs	%	91.28	86.30	86.13	87.90

Table 10 Pressure tightening

Item	Unit	n1	n2	n3	Ave.
Pmax	kN	174.12	274.96	194.68	214.58
Fs	kN	504.00	504.00	504.00	504.00
Ratio to Fs	%	34.54	54.55	38.62	42.57

Table 11 Static

Item	Unit	n1	n2	n3	Ave.
Pmax	kN	167.32	203.44	218.72	196.49
Fs	kN	504.00	504.00	504.00	504.00
Ratio to Fs	%	33.19	40.36	43.39	38.98

Table 12 Threaded screws 400 mm

Item	Unit	Full-screws	Half-screws	difference
Pmax	kN	67.52	53.32	14.20
Py	kN	39.56	25.63	13.93
K	kN/mm	4.57	8.64	-4.07
Fs	kN	504.00	504.00	-
Ratio to Fs	%	13.39	10.57	2.82
P(δ=7mm)	kN	35.16	40.16	-5.00
P(δ=20mm)	kN	55.36	53.00	2.36

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2.4 COMPARISON AND DISCUSSION

Comparing the 400 mm adhesive, we could not see much of an attraction effect from the change to the half-thread. The reason may be that the threads of the half-threads overlapped the joints between the columns, creating a gap on one side. Therefore, it is possible that the compressive tightening performance of the half-thread is higher than that of the present situation. The results suggest that either full or half-threaded screws may be used, but half-threaded screws offer less resistance when driven in and are easier to install, so it is better to use half-threaded screws for installation.

Comparing the one thread adhesive, Pmax was approximately 80 kN higher for the half screw than for the full screw. This is thought to be because the half-screws can tighten under pressure due to the attraction effect of the half-screws. In addition, when comparing the 400 mm adhesive with two screws and the one thread adhesive, Pmax was about 70 kN lower for the one thread adhesive than for the full screw adhesion, but almost the same value as the 400 mm adhesive was observed for the half screw adhesion. This is thought to be due to the higher attraction effect of the half-screw compared to the full-screw, and the longer distance that can be covered by a single screw.

Comparing the 400 mm compression specimens, Pmax was extremely high for the semi-threaded specimens. Comparing the 400 mm adhesive and 400 mm compression, the specifications are the same with or without screws, and all the fracture properties are wood fracture near the adhesive. However, the 400 mm compression with half screws showed higher values. This may be due to the difference in whether both sides fracture at the same time or one side fractures at a time in a piecemeal manner. Although the specific gravity of the materials was combined in such a way that the variation was small, the bending and deviation of the materials were not considered, which may have caused some deviation in the overall results.

Comparing the static and pressure-compacting machines, the pressure-compacting machine showed a slightly higher value, but the static alone showed a proof stress not so different from that of the pressure-compacting machine. In addition, the values for both full and half-threads were higher when pressure-tightening was performed using screws than using a pressure-tightener, suggesting that simple pressure-tightening using screws is possible.

2.5 CONCLUSION

The difference in the pressure-compression performance between the full- and half-threaded screws is thought to be that the half-threaded screw has more of an attracting effect, allowing a larger area to be compressed with a single screw. Although wood breakage near the adhesive occurred in all specifications, and there is a possibility of variation, the results of gluing one full screw and one-half screw indicate that the pressure-compression performance of the half screw is considerably higher. In addition, since the bearing capacity of screws fastened to wood in two-sided shear is the same for full and half screws, and half screws are easier to install, it is thought that half screws should be used in the future. The pressure-compression performance per screw was found to be 800 mm of bonding length (84,000 mm^2 of bonding area) with a single half-screw. It is thought that simple compaction with a screw can prevent brittle fracture by bearing the shear force as a dowel after the adhesive peels off or the wood breaks near the adhesive. The simple press-fitting of wood to wood using screws for wood construction is considered effective, and it is important to further validate this method by considering variations in the method.

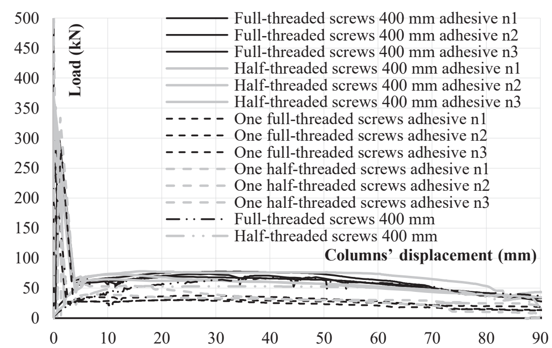

Fig. 36 *Load-displacement curves (Specification with screw)*

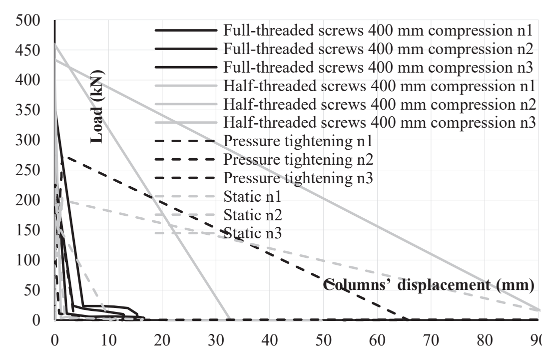

Fig. 37 *Load-displacement curves (Screwless Specifications)*


Fig. 38 *Local buckling (One half-threaded screw adhesive n3)*

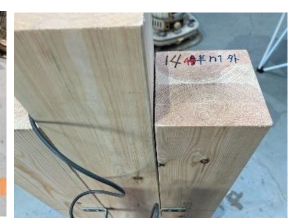
Fig. 39 *Crevice (Half-threaded screws 400 mm adhesive n1)*

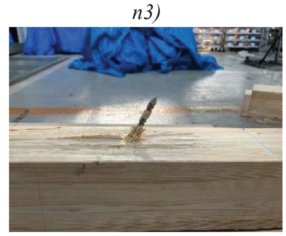
Fig. 40 *Fracture properties of full-threaded screw*


Fig. 41 *Fracture properties of half-threaded screw*

3 FUTURE PLANS

The column-foundation connection was modelled as a rotational spring to analyze whether the structural performance of a sectional column-rigid frame structure could be predicted. SAP2000 was used for analysis. The results showed that the stiffness of the analysis results was low. This may be because the rotational stiffness of the rotating spring was calculated as the moment obtained by multiplying the axial force of the hold down hardware by the distance to the centre of the column, without considering the compression perpendicular to the grain in wood of the column. A reasonable evaluation would have been possible if the compression perpendicular to the grain in wood was considered. Now that the joints have been modelled, we will conduct a column-foundation joint test. The specifications being considered include the use of non-slip plates, non-slip screws in the foundation, changing the foundation from laminated wood to LVL, screws from column to foundation, and the use of conventional construction hardware commonly used in joints. Details of the specifications are shown in Table 13. By including the results of these tests as rotational stiffness in the rotational spring, the structural performance of the sectional column-rigid frame structure can be predicted. After the prediction, sectional column rigid-frame structural tests will be conducted using the same joint specifications to confirm the validity of the analysis.

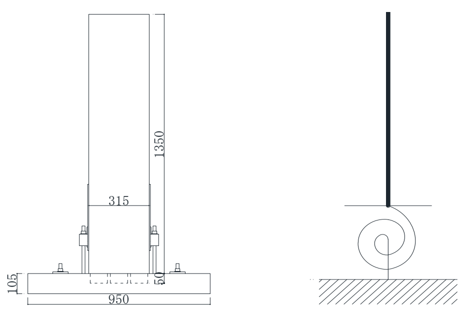

Fig. 42 *Analytical model (left: Cross-Sectional Column Rigid Frame Structure, right: Analytical model)*

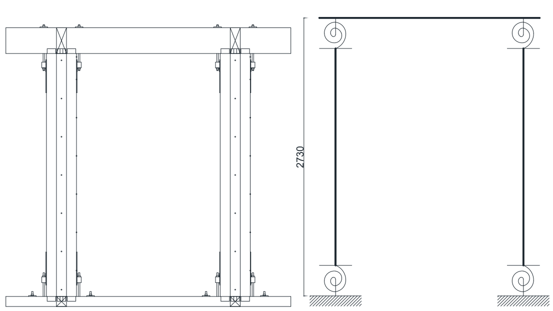

Fig. 43 *Analytical model (left: Cross-Sectional Column Rigid Frame Structure, right: Analytical model)*

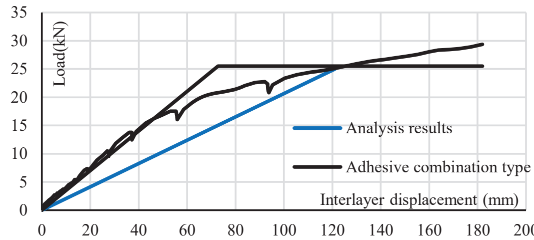

Fig. 44 *Load-displacement curves*

Table 13 *Details of each specification*

Specification	Foundation	HD joint	Additional information
1	European red pine	○	Restraining sink deformation hardware
2	European red pine	○	Restraining sink deformation course thread
3	Laminated Veneer Lumber (LVL)	○	Laminated Veneer Lumber (LVL)
4	European red pine	×	Panelead instead of HD joint.
5	European red pine	○	Jointing hardware for framed structures

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